Further comments on a visual study of pulp floc dispersion mechanisms

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ABSTRACT *A knowledge of fiber and fluid interactions is crucial to the flow management aspects of the design of a paper machine. A visual study of the dispersion mechanism of pulp flocs in a controlled, turbulent Couette flow field was carried out to obtain qualitative information on fiber and fluid interactions. The turbulent Couette flow field was created by a moveable-wall, flow channel system. The dispersion sequences were recorded by high-speed camera, using both monocular and stereoscopic film techniques.*

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Dispersion
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Mathematical models
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Turbulence

In an earlier visual study of the dispersion of artificially produced, softwood pulp flocs in controlled, plane, turbulent Couette flow (*1*), both monocular and stereoscopic film techniques were used. In that report, Lee and Brodkey discussed the mechanisms of the controlled floc formation and of the dispersion. For dispersion, two mechanisms were observed. One mechanism was global, involving deformation, breaking, and fragmentation, and one mechanism was local, involving surface erosion. The effect of the flow field stress on the time and rate of dispersion was studied.

The objectives of this earlier study were to add to the fundamental knowledge of fiber–fluid interactions to help develop flow management concepts that would improve control of fiber-fluid systems. Here, additional information is provided to help in evaluating the fundamental and somewhat idealized approach taken by Lee and Brodkey to problems faced in paper technology.

Summary of results reported previously

Flocculated fiber aggregates, or "flocs," result in nonuniformity in a paper sheet and may cause the sheet to break up during processing. The breakup of fiber flocs in a turbulent flow was of particular interest in the earlier study. In the final stages of papermaking, the pulp suspension is dispersed in a headbox and is forced through a sluice onto a moving screen where the water drains and the sheet forms. The fiber must be uniformly distributed in the suspension during this operation. Regions of voids are detrimental, forming pinholes and resulting in tears.

The authors did not study the flocculation and dispersion process statistically, but they focused instead on the dispersion mechanism of single flocs. A visual technique was employed because of its success in the coherent structures in turbulence studies. By observing the dynamics of the dispersion process, insights were gained as to the interactions of the fiber and fluid systems. With the use of single flocs instead of a suspension, the complication of flocculation was eliminated. First we must know the requirements to break an entangled fiber floc and disperse it in a suspension without the interference of fibers. Then we may proceed to the next step of studying how flocculation affects the dispersion.

The formation of the pulp flocs was achieved in a laminar environment where the fibers were at their sedimentation concentration (about 0.7%) with supernatant water. The formation of pulp flocs under this condition is a process of network disruption followed by aggregate interaction. These flocs were highly entangled and had fairly uniform size and shape. These flocs are expected to be much stronger than the ones in a paper machine because the flow field we used was more favorable for floc formation and the duration of floc formation was much longer. The advantages of using these flocs for studying dispersion were (a) better reproducibility and (b) better uniformity of the flocs.

The zero mean velocity of the flow field provided a nonmoving, convected view of the dispersion process. The entire sequence could be observed without moving the camera with the flow. This advantage allows us to follow the dispersion history rather than observing only instantaneous occurrences.

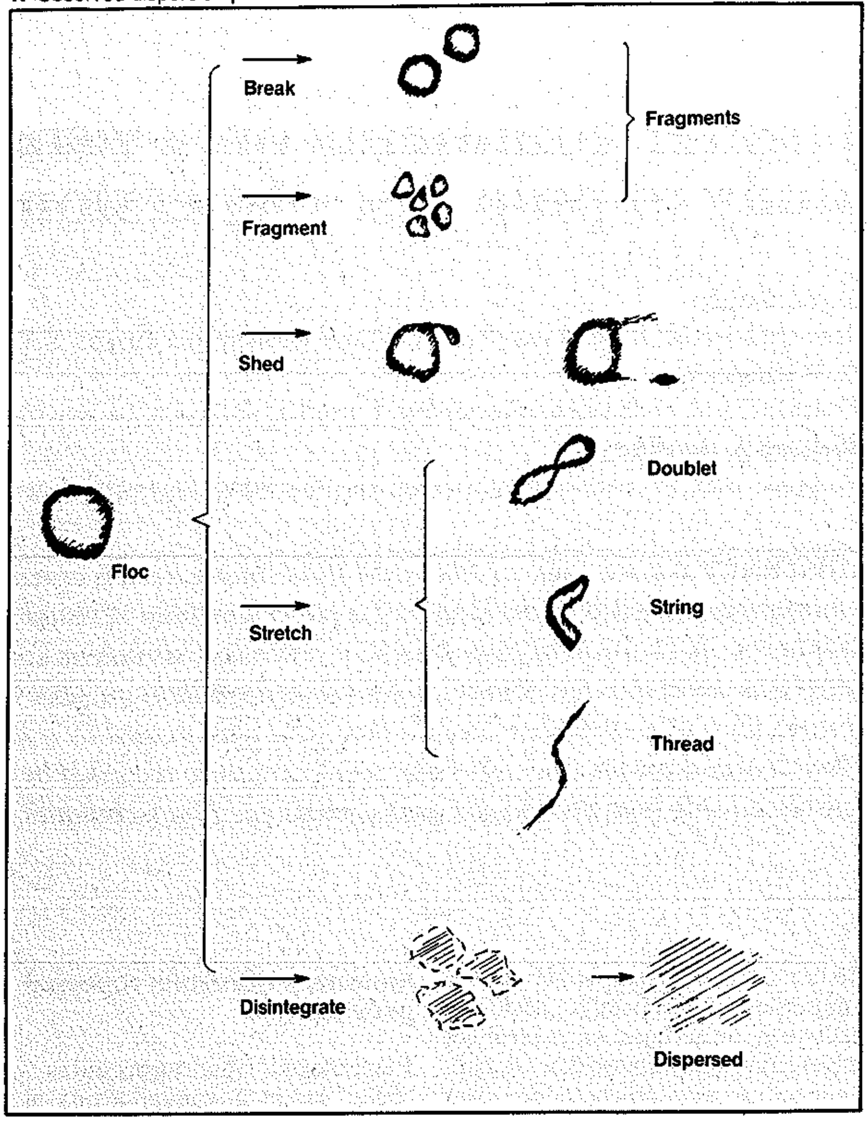
Lee and Brodkey studied dispersion of these flocs in two channel widths, each at four stress levels. There are two major mechanisms involved in the dispersion process of a pulp floc. One mechanism involves the large-scale, global phenomena that include deformation, breaking, and fragmentation of the entire floc. The other is a small-scale local phenomenon of surface erosion which involves only individual surface fibers.

For the global phenomena, the mode of disruption was found to depend on the structure of the floc, the imposed flow field, and the duration of disturbance caused by the surrounding fluid. Only when the net tensile force on the entire floc exceeded the minimum separation did the floc rupture.

The large-scale global disruption is a mechanism for rapid size reduction, and its occurrence is stochastic in nature. The local surface erosion mechanism is a rate process which required lower stresses and occurred over the entire surface of the floc throughout the dispersion process. In this process, the surface fibers are pulled away by small-scale disturbances. It is a slower size-reduction process than the global disruption mechanism, but it is effective and essential for fiber-scale dispersion. Preliminary studies on the rate of erosion suggest that erosion is an exponential decay process for which the rate constant is a linear function of the stress of the flow field.

The time required for complete dispersion of the flocs was dependent on the stress of the flow field. Higher stress levels resulted in shorter dispersion times. The wide distribution of final dispersion times is a result of the stochastic nature of the process and the variations of the strength of the flocs. The difference in channel width did not result in different dispersion time except at the lowest stress studied.

1. Observed dispersion phenomena



Updated results and comments

Floc formation

The concentration of the suspension plays an important role in the formation of flocs. At high concentrations, a fiber network may form as a result of restricted individual fiber movement. Under this condition, the common understanding of flocculation that involves the entanglement of fibers as a result of fiber collision does not apply. Floc formation is the result of network disruption and aggregate compaction.

Jacquelin (*2*) indicated that floc size is associated with the constituent fiber length. Fibers of different lengths were separated by the rolling method. One may postulate that a fiber would not staple to a floc of larger size. In an experiment in which a test rod was placed in the flow stream to catch fiber flocs (*3*), the rod retained flocs larger than its diameter, while the smaller ones slipped by.

The compaction of flocs also reduces their ability to further flocculate, because of the "smoothing" effect, in which the surface fibers bend and adhere to the floc, reducing the surface roughness. Once the floc surface is smoothed, fibers and fragments can no longer anchor to it. In a system of fiber suspension with a narrow size distribution, the maximum floc size would be close to the fiber length.

The process of formation of flocs is a size-reduction process in which a fiber mat separates into aggregates that interact to rearrange internal fibers and remove loose surface fibers to form their final stable size and shape. This appears to be the case at

I. Operating conditions for each case

Case	Channel width, cm	Belt velocity, cm/s	Stress level, dyne/cm²	No. of runs recorded
I-1	1.0	53	7.5	15
I-2	1.0	106	25.7	23
I-3	1.0	159	53.2	31
I-4	1.0	212	89.2	9
II-1	2.0	58	7.5	14
II-2	2.0	115	25.7	17
II-3	2.0	172	53.2	19
II-4	2.0	229	89.2	11

II. Final dispersion times

Case	No of samples	Average disp. time	Standard deviation
I-1	n.d.	n.d.	n.d.
I-2	29	0.84	0.39
n	20	0.97	0.39
s	9	0.57	0.20*
I-3	41	0.42	0.20
n	29	0.49	0.19
s	12	0.26	0.11*
I-4	9	0.25	0.06
n	6	0.24	0.07
s	3	0.28	0.03
II-1	9	1.91	0.58
II-2	17	0.87	0.38
n	12	1.00	0.38
s	5	0.56	0.08*
II-3	21	0.47	0.15
n	9	0.51	0.22
s	12	0.44	0.07
II-4	6	0.32	0.14

n = not influenced by injection.
s = shattered by injection.
n.d. = no dispersion.
*n and s are significantly different at 5% confidence limits.

least under the conditions studied and may also be the case in previous studies on fiber suspension flow.

The phenomenon of the mixed flow regime in which mixing is at the aggregate level (*4*) and reports concerning the doubtful existence of fully turbulent suspension flow in pipes (*5*, *6*) suggest that floc formation is mainly due to network fragmentation rather than to interaction at the fiber level. However, in those studies, the flocs were not as highly entangled; the flow fields did not permit the time necessary for formation to proceed to such an extent.

When a 0.5% suspension was rolled at about 100 rpm in a 12-cm-diameter bottle (with a peripheral velocity of about 60 cm/s), the suspension on a large scale was uniform as a result of turbulent mixing. The fibers had relative motion, and flocculation resulted from fiber collision and entanglement. A grainy appearance was probably caused by the coiling of the fibers. The factors that determine the floc size might be the turbulence characteristics and the effective fiber length. The high-stress field prevented the formation of large flocs. The effective fiber length was due to fiber coiling in the shear gradient.

Kerekes and Pye also observed a grain structure in a suspension downstream of a high grid turbulence (*7*). Studies on a high-turbulence headbox (*8*) indicated that fine-scale flocs resulted in lower machine-direction and cross-direction strength: these fine-scale flocs may also be attributed to this self-coiling phenomenon. A simulation of laying fibers of a fixed length at random showed that nonuniformity is more pronounced when the fibers are coiled (*9*).

Floc dispersion

The turbulent flow field between two oppositely moving belts has an S-shape velocity profile. The average velocity across the flow is zero, and there is little mean velocity or mean shear in the turbulent central core region. This region is characterized by a turbulent zone without a mean velocity or mean gradient in velocity. Of course, there are intense turbulent fluctuations and local gradients. The stress, however, is uniform everywhere and depends only on the separation distance between the belts and the Reynolds number of the flow. The constant value of the stress field is independent of the state of the flow (laminar or turbulent) and the nature of the fluid (Newtonian or nonNewtonian).

The actual stress levels were calculated from a drag coefficient correlation and are described in detail elsewhere (*1*). The equation (*10*) is

$$(2/C_f)^{1/2} = 5.75 \log [N_{Re} (C_f/2)^{1/2}] + 7.15 \quad (1)$$

where

C_f = drag coefficient

N_{Re} = Reynolds number.

The stress itself is defined in the normal manner as

$$\tau = (1/2)\rho C_f U^2 \quad (2)$$

where

τ = shear stress

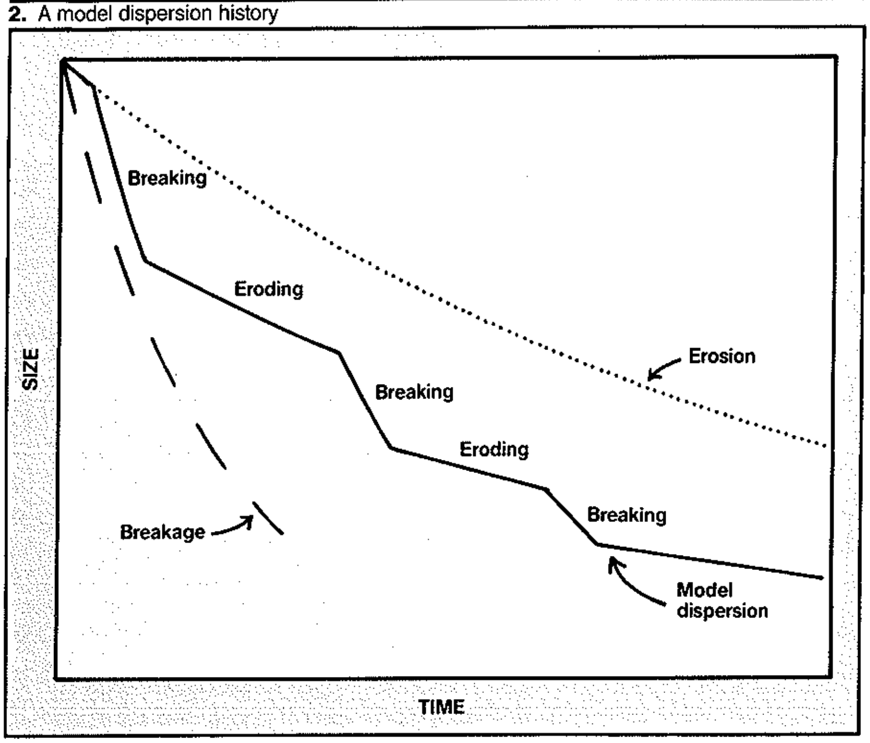
ρ = density

U = belt velocity.

A floc after being rejected into the flow channel is subjected to these mean stresses as caused by the flow field. Since the floc is unable to follow the motion of the surrounding fluid, there exists a relative velocity between the floc and the fluid. This relative velocity results in direct stresses on the floc. Some typical values of the parameters of the flow for the conditions studied are presented in **Table I.**

At low Reynolds numbers, the velocity gradient is less steep and the strain rate is small; therefore, breaking does not always occur. Long-lasting doublets and attached fragments are representative of this category. Doublets remaining in coherent rotational motion indicate the existence of slow, large-scale turbulence in the core region that entrains the entire floc. The floc follows the motion of the slow eddy with little relative velocity. Hence, erosion rate is also small and may not occur at all. As the stress of the flow field increases, the frequency of the occurrence of breaking and fragmentation increases. **Figure 1** is a sketch of the types of breakup behaviors observed (*1*).

2. A model dispersion history



Key conclusions

Some of the conclusions are as follows.

Breakage fragments sometimes moved in directions opposite the local mean flow direction.

Erosion of surface fiber progresses at a higher rate because of the higher strain rate. Thus, the total dispersion time is reduced.

When subjected to stresses that result in a net tensile force, the floc is elongated, and the fibers are aligned in the direction of the tensile force. The resulting thread can be as long as several fiber lengths, which could be caused by the staggering of the aligned fibers or the coherence of the turbulent structure that caused the stretching.

Breaking of the thread does not always occur immediately, because it depends on the duration of the applied tensile force and on the coherence of the surrounding turbulent field.

When the external force ceases, the stringy structure remains at its final strained state. An elastic material would recoil, but recoil has not been observed.

Stretching of the entire floc immediately after injection is rare except for the cases where the floc structure is quite loose. These loose flocs are merely fragments of the initial sedimented fiber network that underwent the flocculation process to a lesser extent.

The rate of size reduction of the floc due to erosion is expected to be related to the size of the floc. Size not only determines the total exposed surface area available for erosion, but it also has an effect on the relative velocity. As the aggregate becomes smaller, it becomes more stable because it is able to follow more closely the motions of the surrounding fluid. Hence, the velocity differential is reduced, and the rate of erosion falls as the aggregate becomes smaller.

The global disruption and the surface erosion of the floc reduced its size to a point where the distinction between the mechanisms no longer exists. At this point, any deformation involves the fragment as a whole. The effective floc-scale turbulence at this stage is small-scale turbulence. The dispersion of this final aggregate appears as an expansion into individual fibers. Existence of fine-scale turbulence is essential in achieving this final dispersion.

Time and rate of dispersion

The average total time required to disperse the pulp flocs at various stress levels were given elsewhere (*1*). The difference due to the width of flow channel was statistically insignificant at a 5% confidence limit except for the lowest stress level, where no complete dispersion was observed for the narrow channel. At higher stress levels, there was an effect of injection breakage.

Injection breakage is equivalent to introducing smaller flocs into the stress field and is a relatively fast process. Even though breaking is fast for size reduction, it still requires considerable time when the stress level is low. High stress and rapid breaking at the beginning is favorable for dispersing the floc, and it shortens the final dispersion time to that normally attainable at higher stress levels.

Information on the final dispersion time enables one to interpolate the results for the same initial size in the same flow field for the same type of floc. It does not tell us anything about the history of the dispersion process. Rate information is essential before a model can be developed to predict the results. For this reason, attempts had been made to study the possibility of extracting rate information from the film records.

Details of the final dispersion times are given in **Table II**. At the high stress of Case I-4, the flow field caused initial breaking as fast as the injection, and the difference becomes insignificant. The difference for the wider channel is similar except that it becomes insignificant at the lower stress level of Case II-3. A plot of the average dispersion time (without the n or s information) is given elsewhere (*1*).

A simple model was introduced (*1*) that appears to be valid for the erosion process. This model should also be applicable to the global disruption; even though the occurrence may be stochastic, on a larger time scale the process is also a decay process. In the form of exponential decay, this process may be expressed as

$$S/S_0 = \exp[-k(t - t_0)] \quad (3)$$

where

S = size

S_0 = initial size

k = the rate constant of the global disruption process

t = time

t_0 = initial time.

This is represented in graphic form in **Fig. 2**, where the broken line represents decay by global disruptions and the dotted line represents the erosion process. A model dispersion process is represented by the solid line. The figure suggests that a complete model may be one that applies a pseudo-first order model at the beginning and switches over to an erosion model when the distinction between a global disruption and erosion is no longer significant.

Another possible model would be a direct simulation of the process in which the stochastic process of global disruption is incorporated in the rate process. For all the cases studied, such breakup occurred only several times during the entire process. A direct approach is therefore a feasible possibility.

Literature cited

1. Lee, C. W. and Brodkey, R. S., AIChE J. 33: 297(1987).
2. Jacquelin, G., U.S. Patent 3,679,542 (July 25, 1972).
3. Parker, J. D., Tappi 44(4): 162A(1961).
4. Andersson, O., Svensk Papperstid. 69(2): 23(1966).
5. Hemstrom, G., Moller, K., and Norman, B., Tappi 59(8): 115(1976).
6. Raij, U. and Wahren, D., Svensk Papperstid. 67(15): 186(1964).
7. Kerekes, R. J. and Pye, I. T., Turbulent flow of fiber suspensions during papermaking, Report Proj. 234, Pulp and Paper Res. Inst. Canada, 1981, p. 62.
8. Ryti, N., Paulapuro, H., and Rath, B., Proc. Intl. Symp. on Paper Machine Headboxes (A. S. Majuondar, Ed., McGill University), Montreal, Canada, 1979, p. 162.
9. Lee, C.-K. W., A visual study of fiber and fluid interactions, Ph.D. thesis, The Ohio State University, Columbus, Ohio, 1982.
10. Leutheusser, H. J. and Chu, V. H., J. Hydraulics Division, Proc. ASCE, HY-9: 1269(1971).

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